PROGRESS REPORT

PR 91570-510-8

For the Period of February 1, 1964, through February 29, 1964

DEVELOPMENT OF A HYDROGEN-OXYGEN SPACE POWER SUPPLY SYSTEM

NASA Contract NAS 3-2787

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INTRODUCTION

This report is issued to comply with the requirements of NASA Contract, NAS 3-2787, and to report the work accomplished during the period February 1 through February 29, 1964. The objectives of this program are to conduct engineering studies, design, fabrication, and test work culminating in the design of an auxiliary power generation unit.

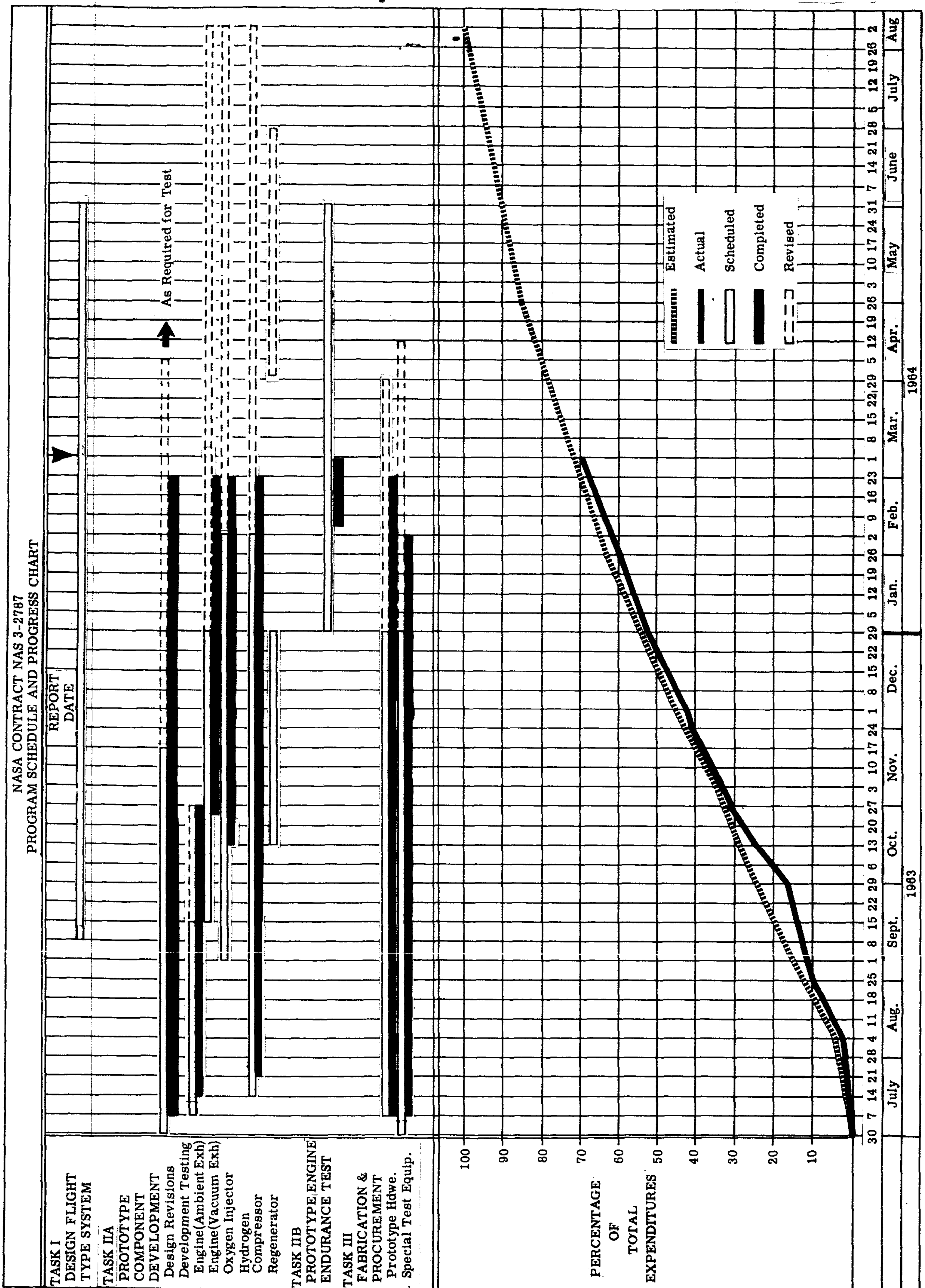
This contract, NAS 3-2787, is a continuation of NASA Contract NAS 3-2550.

PROGRAM SCHEDULE

The program schedule shown in Fig. 1 has been revised to reflect changes in the program plans resulting from a technical review meeting between NASA and Vickers Inc. on January 16 and 17, 1964. Component development and endurance testing will be extended through July, 1964. Flight system design work will continue to be deferred until additional development and endurance testing have been accomplished.

FLIGHT TYPE POWER SYSTEM DESIGN

No work was scheduled during this reporting period on the flight type power system design because of technical direction from the NASA Technical Program Manager.


NASA CONTRACT NAS 3-2787
PROGRAM SCHEDULE AND PROGRESS CHART
REPORT DATE
TASK I
DESIGN FLIGHT TYPE SYSTEM
TASK IIA
PROTOTYPE COMPONENT DEVELOPMENT
Design Revisions
Development Testing
Engine(Ambient Exh)
Engine(Vacuum Exh)
Oxygen Injector
Hydrogen Compressor
Regenerator
TASK IIB
PROTOTYPE ENGINE ENDURANCE TEST
TASK III
FABRICATION & PROCUREMENT
Prototype Hdwe.
Special Test Equip.
As Required for Test
PERCENTAGE OF TOTAL EXPENDITURES
100
90
80
70
60
50
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10
Estimated
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30 7 14 21 28 4 11 18 25 1 8 15 22 29 6 13 20 27 3 10 17 24 1 8 15 22 29 5 12 19 26 2 9 16 23 1 8 15 22 29 5 12 19 26 3 10 17 24 31 7 14 21 28 5 12 19 26 2
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Fig. 1

PROTOTYPE COMPONENT DEVELOPMENT

Engine

Design and Fabrication

The following design and fabrication was accomplished during this reporting period.

1. Fabrication of parts for the new piston and cylinder design (shown in Fig. 3, PR 91570-510-5) are scheduled for completion by March 6, 1964.

2. The cooled cylinder head insert drawings have been changed for use with the new cylinder design. Two blanks are being fabricated.

3. The piston of the No. II engine was reworked to reduce the possibility of dome leakage and dome securing screw failure. The securing screw was replaced with a larger diameter Inconel bolt. The bolt was inserted from bottom of the piston and silver brazed to the top side of the piston. Tension loading is taken by the bolt head, the braze serving only as a seal. The dome was screwed [illegible] the piston, and the bolt finished flush with the top dome surface.

4. A cast iron cylinder of the new design configuration is being fabricated as an alternate to the T-15 tool steel cylinder.

5. One cylinder head insert (of the present cylinder configuration) was reworked to hold catalyst pellets.

6. The squish type cylinder head, shown in Fig. 2, P/N X612208, is being fabricated for use with the new cylinder configuration. The two drilled holes are for catalyst pellets.

7. One H_2 valve cap was reworked for mounting the Kistler pickup on the top of the cylinder head ring. An adapter is being fabricated for mounting the Photocon pickup in the same location.

8. Two O_2 injector, split drive, quill shaft-tube-flange assemblies have been completed successfully. One assembly has an aluminum oxide flame plated shaft and the other a nonplated shaft.

9. A guide type (nonspring loading) O_2 injector poppet retainer was designed and fabricated.

10. Parts are being fabricated for the revised O_2 injector rocker arm shown in Fig. 3. This design provides more actuating and guide bearing area; allows for angular self-alignment of the poppet; and allows for bench adjustment of lash without grinding of the poppet.

11. Oilite bushings were made to replace O_2 injector rocker shaft needle bearing for the split drive configuration. One rocker shaft was reground (to remove Brinell damage) for use with these bushings.

12. The crank case of Engine No. II was reworked for use with an O_2 injector with a split drive.

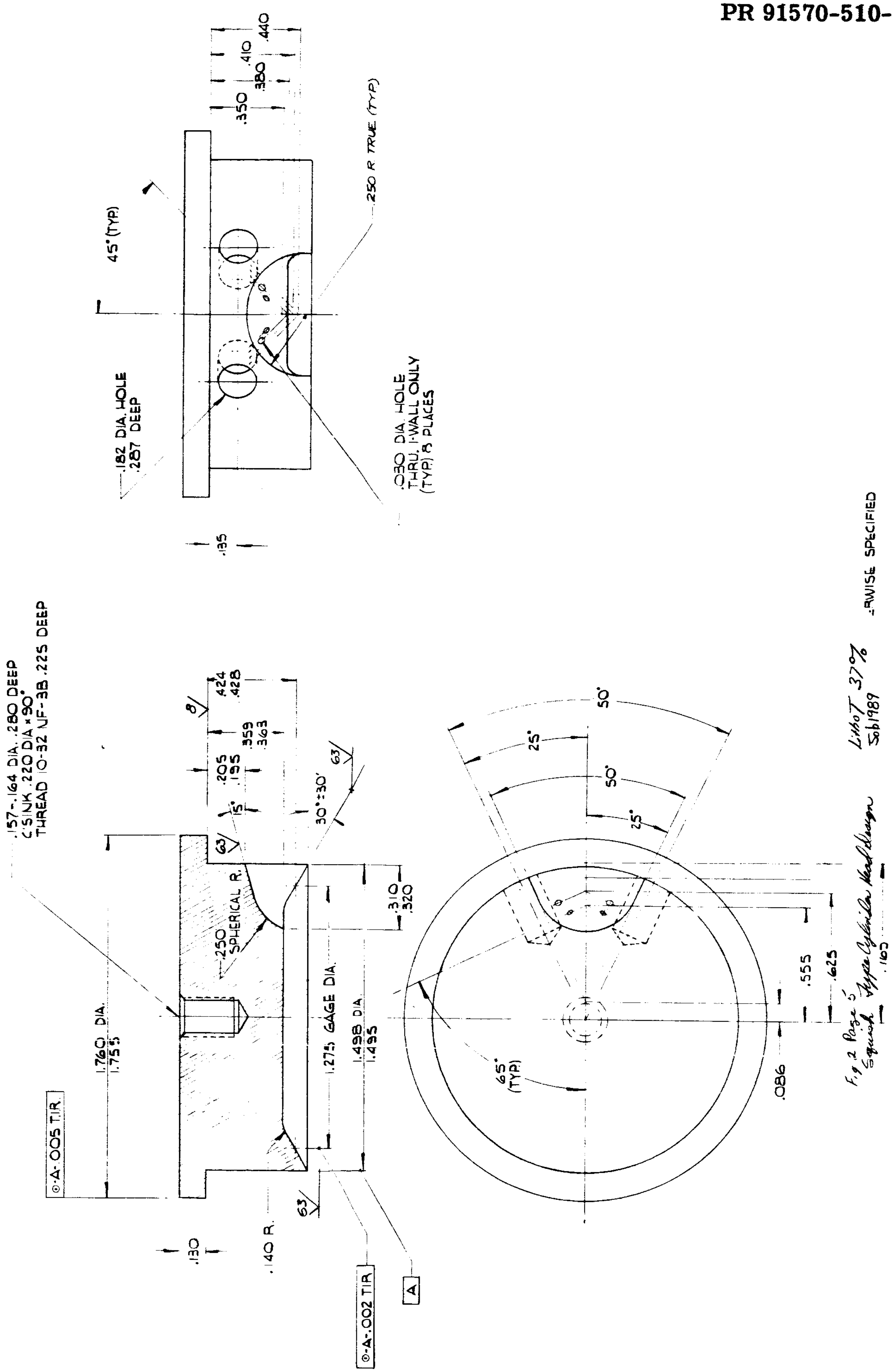


Fig. 2 - Squish Type Cylinder Head Design

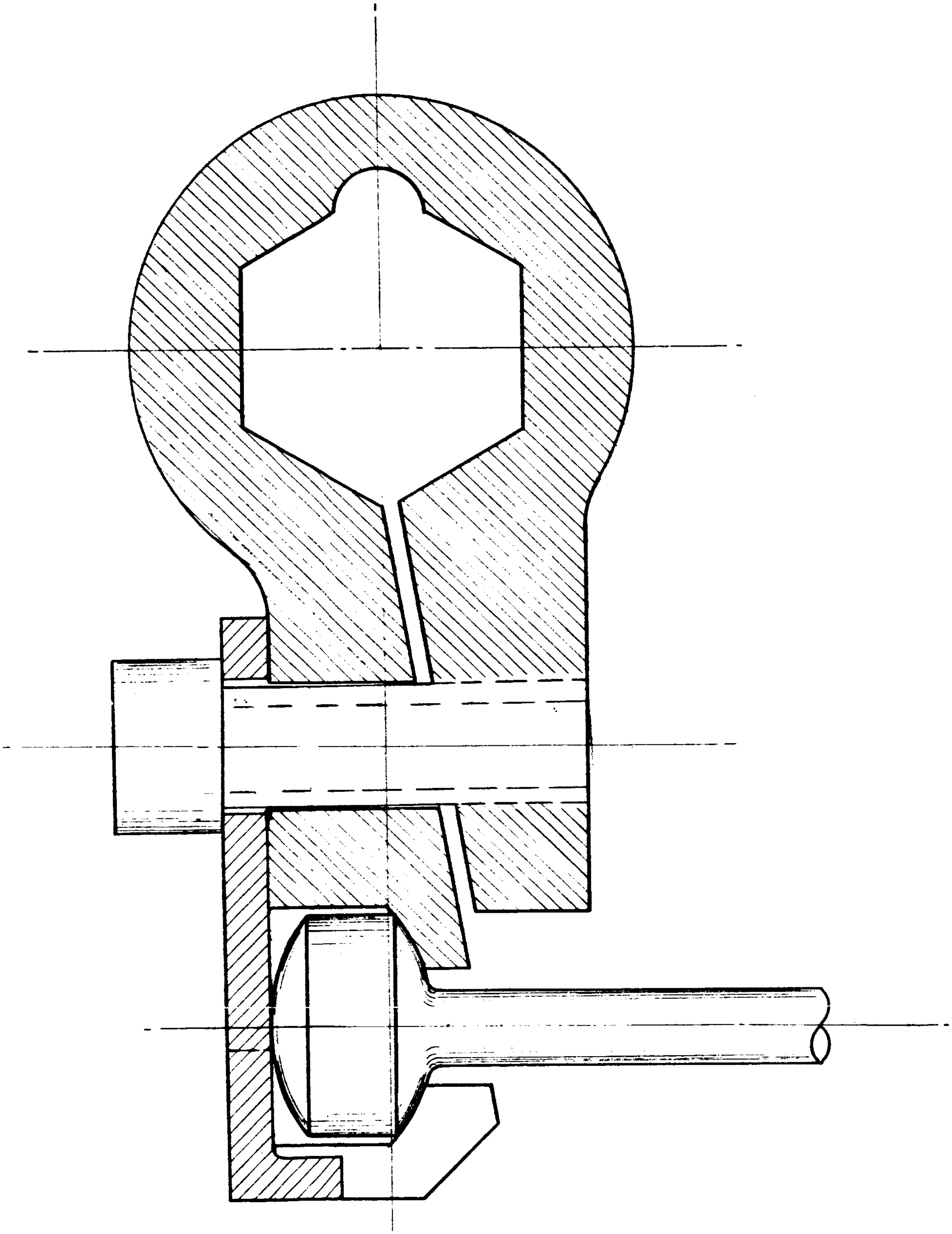


Fig. 3 - Redesigned O_2 Injector Rocker Arm

13. Drawings were made for reworking the engine crankcase and cylinder head rings for use with the new cylinder design.

14. A third O_2 injector body was reworked for a quill shaft bushing.

Assembly

An additional small diameter metal "O" ring was placed between the piston dome and piston body of the No. 3 buildup of Engine No. I to reduce the possibility of leakage through the piston.

Engine No. I was completely disassembled and inspected after 14 hours of endurance testing (8 hours continuous plus 6 hours continuous).

The following modifications were made during the No. 4 buildup of Engine No. I:

1. The piston pin retainer cups were reworked to prevent contact and axial loading of needle bearings.

2. The large seating diameter poppet of the H_2 injector was reground to a sharper angle so that it would seat at a smaller diameter to reduce its effective area thus increasing the H_2 supply pressure which could be applied without causing the valve to blow open.

3. The O_2 injector was changed because the rocker shaft became Brinelled by the needle bearings.

The No. 4 buildup of Engine No. I was run for the rest of the month without complete teardown. The following modifications were made after a 12-hour endurance run:

1. The large seating diameter H_2 valve poppet was reground because of warpage which caused slight leakage.

2. The H_2 valve springs were replaced because they had taken a permanent set thus reducing the permissable H_2 supply pressure.

3. The O_2 injector poppet retainer spring was replaced with guide type retainers for evaluation.

4. The cooled cylinder head insert was replaced with a noncooled insert holding catalyst pellets.

The No. 3 buildup of Engine No. II is scheduled to be complete on March 4, 1964. This buildup will have: the split drive O_2 injector with Oilite rocker shaft bearings; the piston described in Item 3 of Design & Fabrication; and an H_2 valve with a heat shield.

The No. 5 buildup of Engine No. I will incorporate the new cylinder configuration.

Performance Testing

A total of 41.8 hours hot running time and 4.0 hours cold motoring time was accumulated during the month of February 1964. Three endurance tests were run. All testing was accomplished on the third and fourth buildups of Engine No. I.

Performance tests during this report period were confined mainly to qualitative checks on the feasibility of various operating modes, and to checking out timing conditions to be used during endurance tests.

The three-hole oxygen injector nozzle (three - 0.030" dia. holes) was used with the 7% clearance volume cooled cylinder head, using low pressure nitrogen instead of Dowtherm as the head coolant. Results are shown in Entries 8 through 14 of Table I and P-T traces are shown in Figs. 7 and 8.

Oxygen timing was advanced 5° to determine if greater valve overlap would improve performance by inducing better mixing or more turbulence during combustion (See Table II). While power level was down (compare Entires 11 and 12, and Entries 9 and 14, of Table I) BSPC was equal or better. Therefore in subsequent runs somewhat more valve overlap was used than has been used in the past.

A higher than usual back pressure was necessary to avoid misfiring. The cause of this is not known, but minimum allowable back pressure appears to be a function of head temperature, mixture ratio, blowdown area, and injector configuration. The three hole injector does not appear to give significantly different results than a single hole injector, but more data is needed.

Inlet hydrogen was routed through the cylinder head before admission to the engine (Entry 15, Table I). Fig. 9 shows a P-T trace photographed during this test. The strange appearance of the hydrogen inlet pressure peak may be due to resonance. It was possible to hold the cylinder head temperature to 1200°F and achieve a hydrogen temperature of 400°F under the timing conditions of this test. The engine was rather sensitive to slight changes in propellant flow due to the coupling effect between the inlet hydrogen and head temperatures. Further investigation

TABLE I

ENGINE PERFORMANCE DATA - February 1964

Entry	Time Date	Time Hour	Oper. Cond. No.	H_2 Inlet Temp °F	H_2 Inlet Press psig	O_2 Inlet Press psig	Speed rpm	BMEP psi	Power HP	BSPC lb/hp-hr	O/F lb/lb	% Heat Rejected	Vacuum mm Hg
1	2-5	8:50	1	430	300	760	3010	120	2.50	2.02	1.59	79	160
2	2-5	11:00	1	400	300	670	3020	121	2.51	2.10	1.70	83	175
3	2-5	2:00	1	500	300	550	3000	110	2.27	2.13	1.32	76	157
4	2-5	4:00	1	500	300	550	2960	106	2.16	2.27	1.44	89	135
5	2-6	1:45	1	100	300	700	2990	134	2.76	2.11	1.40	64	166
6	2-6	4:00	1	115	300	620	3010	134	2.75	2.10	1.35	60	157
7	2-6	6:00	1	460	300	490	2970	109	2.22	2.20	1.31	68	164
8	2-20	11:10	2	100	300	800	4020	137	3.77	2.00	0.87	47	345
9	2-20	11:16	2	100	300	800	4010	139	3.84	1.95	0.87	43	343
10	2-20	11:30	2	100	300	540	3010	130	2.69	2.17	0.84	48	415
11	2-20	11:51	2	480	300	540	2990	124	2.55	1.88	0.90	56	295
12	2-20	4:15	3	515	300	555	2990	106	2.18	1.82	0.99	57	238
13	2-20	4:27	3	510	300	570	4000	101	2.78	1.77	0.74	40	325
14	2-20	4:32	3	125	300	600	4000	110	3.01	1.92	0.74	29	357
15	2-21	2:17	4	402	300	825	3020	129	2.68	2.00	1.50	67	292
16	2-21	4:35	5	100	300	900	4000	133	3.65	1.90	1.11	47	346
17	2-21	4:40	5	100	300	800	3000	142	2.94	1.92	1.31	57	278
18	2-24	9:15	6	475	300	860	3000	125	2.57	2.29	1.08	67	319
19	2-24	11:48	6	480	300	880	3000	127	2.62	2.03	1.55	68	355
20	2-24	2:00	6	500	300	800	3010	125	2.58	2.04	1.45	67	320
21	2-24	6:00	6	510	300	660	2980	118	2.41	1.95	1.23	64	315
22	2-27	3:08	7	510	300	520	2970	97	1.97	2.42	0.73	62	170
23	2-27	3:33	7	480	300	610	3000	105	2.15	2.34	0.85	66	96
24	2-28	10:00	8	510	300	535	3010	123	2.56	1.78	0.98	58	167
25	2-28	11:30	8	500	300	580	3010	123	2.54	1.73	1.10	65	202
26	2-28	1:28	8	490	300	520	3010	111	2.29	1.94	0.99	79	210
27	2-28	3:25	8	490	300	410	2990	109	2.25	1.85	0.98	60	200
28	2-28	6:30	8	475	300	430	3010	111	2.28	1.91	0.98	65	180

into this type of regenerative cooling is planned. In Entries 16 and 17 (Table I) the cylinder head is cooled with high pressure (300 psi) nitrogen. It was planned to use nitrogen cooling for the 12-hour endurance test but since no advantage over Dowtherm cooling was apparent unless a high head temperature was allowed, Dowtherm was used.

An uncooled squish-type cylinder head, with a channel-shaped combustion chamber and provisions for containing catalyst pellets in the head, was run. Data are given in Entries 22 and 23 of Table I, and in Fig. 11. BSPC was high due to a high hydrogen flow, and power was low. The catalyst pellets disintegrated during the run. It was possible to run at a very low back pressure if head-temperature was set at 1500°F, and smooth combustion at 90 mm Hg back pressure was achieved. Late ignition rather than misfiring occurred as back pressure was reduced.

Endurance Test No. 1

Engine No. 1 (3rd buildup) was run for 8.1 hours on February 5, 1964, starting at 7:59 a.m. and stopping at 4:06 p.m. An engine speed of 3000 rpm and a power level of 2.3 - 2.5 hp were attained. Representative test data are given in Entries 1 through 4 of Table I and in Figs. 4, 5, and 6. Data were recorded every ten minutes for the first hour and at half hour intervals thereafter. This engine had one hour of checkout time prior to the endurance test.

The engine ran well during this test. Cylinder head temperature was maintained at 1000°F, and cylinder wall temperature at 400°F. Heated hydrogen and a vacuum exhaust were used. Exhaust pressure averaged 150 mm Hg, and could not be reduced below 130 mm Hg without misfiring. Oxygen injector flow showed a tendency to increase during the test, requiring a drop in oxygen inlet pressure from its initial value of

760 psi at 8:00 a.m. to a final level of 550 psi at 1:00 p.m. Pressure was held at this level for the remainder of the run. Oxygen flow was occasionally erratic after 1:00 p.m.

Two test set-up malfunctions occurred during this test. The Kistler pressure transducer developed a delayed and greatly damped response and the hydrogen heater, due to a malfunction of its control system, allowed inlet hydrogen temperature to oscillate between the limits of 340°F and 510°F within a period of about five minutes.

The engine was inspected on the morning of February 6. The oxygen injector lift had been originally set at 0.0125" and was found to be 0.0123" (measured cold overnight). Since no malfunctions appeared, the engine was run for an additional six hours, starting at 1:25 p.m. February 6, and stopping at 7:31 p.m. Heated hydrogen was used in the last 3 hours of this run. A vacuum exhaust was used throughout the run. It was again necessary to vary oxygen pressure during the test, from 700 psi to a low of 490 psi, and then back to 540 psi. Data are given in Entries 5 through 7 of Table I. After this run the engine was completely dismantled and inspected.

Endurance Test No. 2

Engine No. I, fourth buildup, was run for 12.2 hours on February 24, 1964, starting at 8:40 a.m. and stopping at 8:51 p.m. This buildup had accumulated 3.6 hours of performance testing on February 20 and 21 prior to this run. The three hole oxygen injector nozzle was used. Timing figures are given in Table II.

Conditions were similar to those experienced in the earlier run, with the same slow changes in injector calibration. Power level and BSPC were both improved as a result of the slightly greater admission. Some test results are given in Entries 18 through 21 of Table I. The hydrogen heater functioned normally.

TABLE II

ENGINE OPERATING CONDITIONS

1. Number one engine, third buildup
   H_2 timing 5° BTDC - 35° ATDC
   O_2 timing 15° ATDC - 55° ATDC
   Clearance volume 8.5% of displacement
   0.054" oxygen injector nozzle
   Dowtherm cooled cylinder head

2. Number one engine, fourth buildup
   H_2 timing 5° BTDC - 40° ATDC
   O_2 timing 20° ATDC - 60° ATDC
   Clearance volume 8.5%
   Three hole injector nozzle (0.030" diameter holes)
   Cylinder head cooled by 250 psi nitrogen gas

3. Same as No. 2, except for timing:
   H_2 timing 5° BTDC - 40° ATDC
   O_2 timing 15° ATDC - 55° ATDC

4. Same as No. 2, except for timing:
   H_2 timing 5° BTDC - 40° ATDC
   O_2 timing 19° ATDC - 59° ATDC
   Hydrogen cooled cylinder head

5. Same as No. 4, except for nitrogen cooled cylinder head

6. Same as No. 4, except for Dowtherm cooled cylinder head

7. Number one engine, fourth buildup
   H_2 timing 5° BTDC - 30° ATDC
   O_2 timing 8° ATDC - 48° ATDC
   Clearance volume 9.0%
   Uncooled (radiation cooled) head with provision for catalyst pellets in head

8. Same as No. 7 except for timing;
   H_2 timing 5° BTDC - 35° ATDC
   O_2 timing 13° ATDC - 53° ATDC

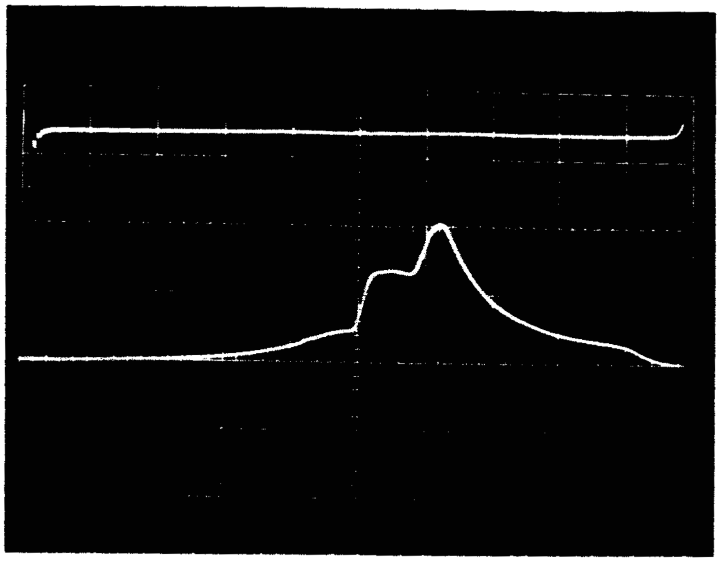


Fig. 4
2-5-64 8:10 am

'8-hour endurance test, after 10 minutes operation. O_2 pressure 800 psig.

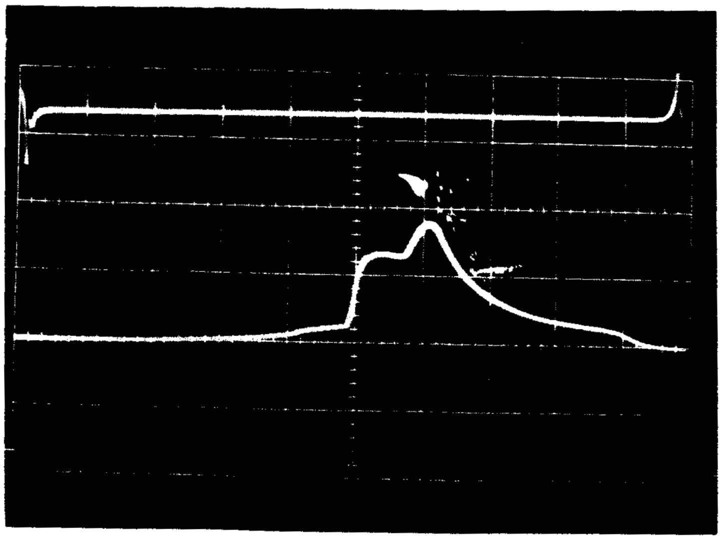


Fig. 5
2-5-64 8:50 a.m.

8-hour endurance test. Entry 1 of Table I.

O_2 inlet pressure 760 psig.

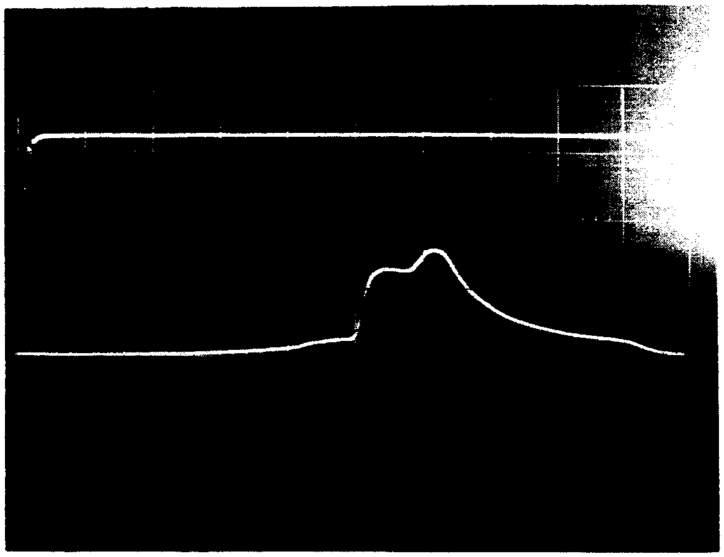


Fig. 6
2-5-64 2:00 p.m.

8-hour endurance test. Entry 3 of Table I.

O_2 inlet pressure 550 psig.

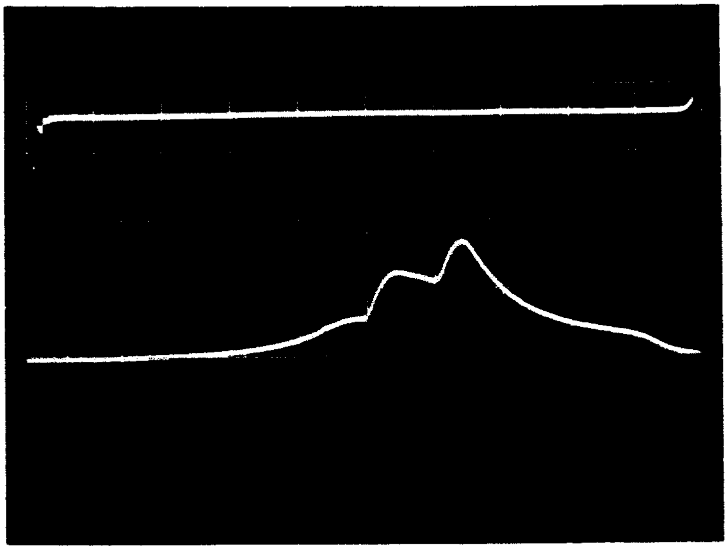


Fig. 7
2-20-64 11:16 a.m.

Entry 9, Table I
4000 rpm
3.84 hp
BSPC = 1.95 lb/hp-hr
O/F = 0.87
3-hole injector nozzle, nitrogen cooled cylinder head.

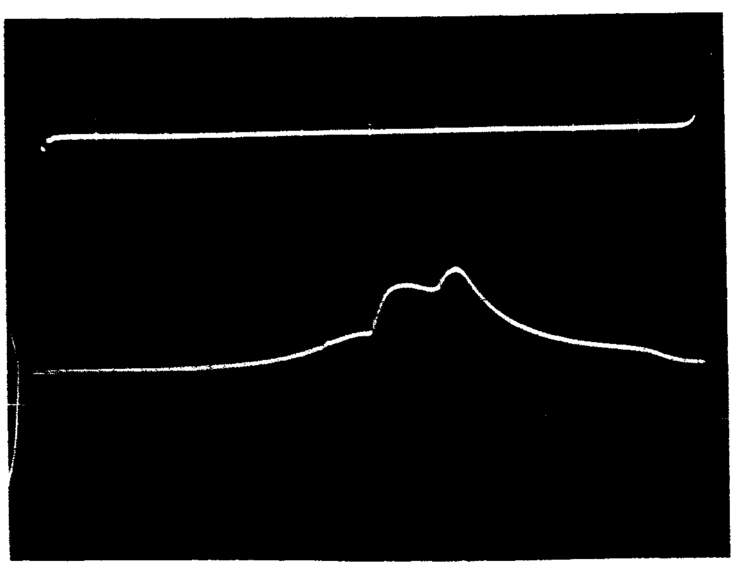


Fig. 8
2-20-64 4:27 p.m.

Entry 13, Table I
4000 rpm
2.78 hp
BSPC = 1.77 lb/hp-hr
O/F = 0.74
3-hole injector nozzle, nitrogen cooled cylinder head, large valve overlap.

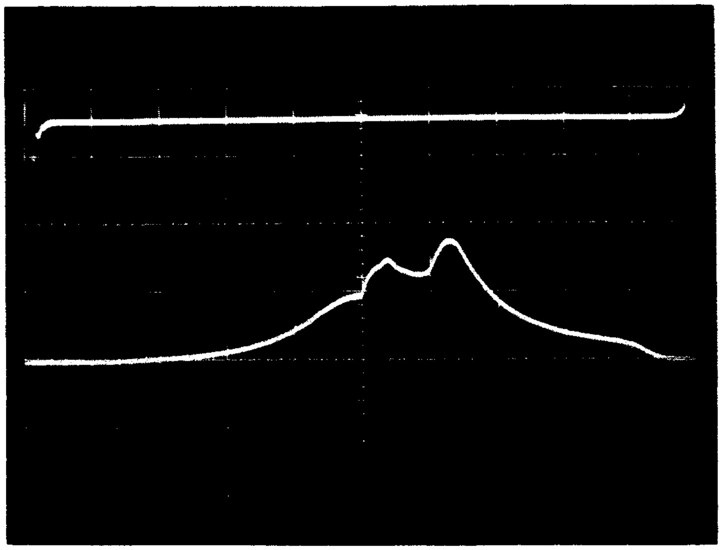


Fig. 9
2-21-64 2:09 p.m.

Cylinder head cooled by inlet hydrogen. Ambient exhaust pressure.

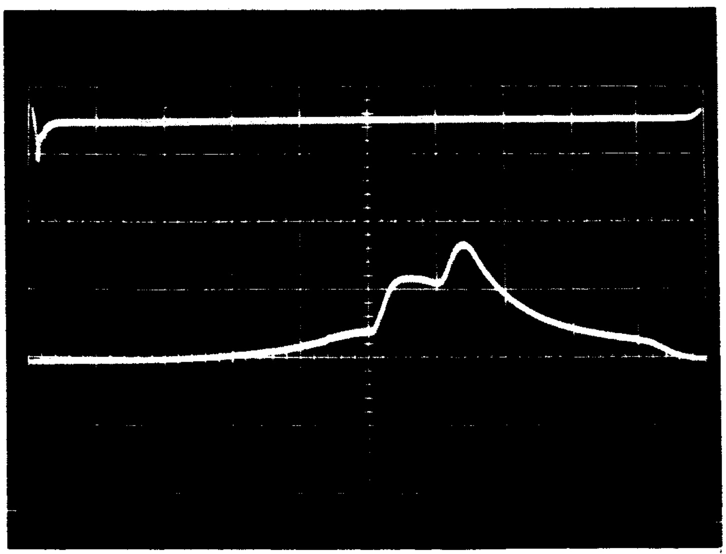


Fig. 10
2-24-64 9:15 a.m.

Entry 18, Table I

12-hour endurance test.

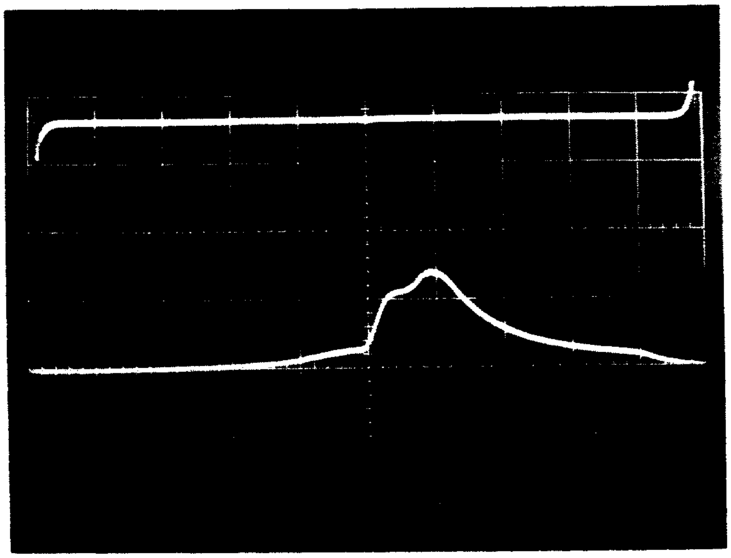


Fig. 11
2-27-64 3:08 p.m.

Entry 22, Table I
3000 rpm
1.97 hp
BSPC = 2.42 lb/hp-hr
O/F = 0.73
Uncooled head with catalyst in head. 1430°F head temperature.

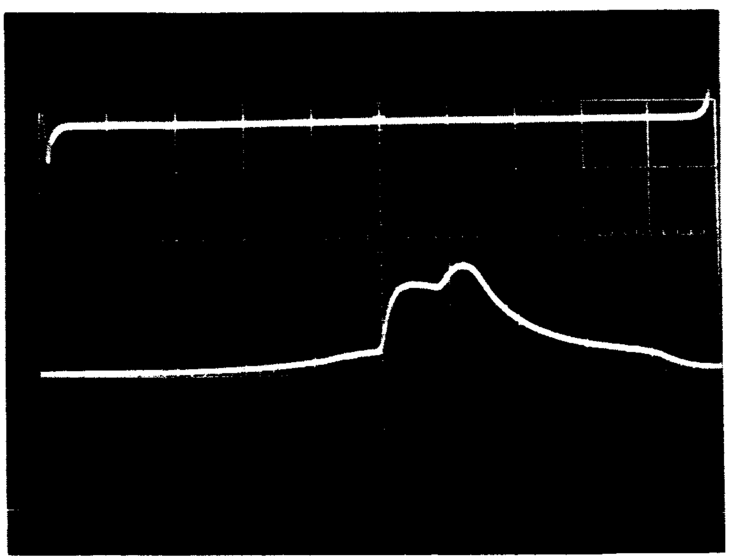


Fig. 12
2-28-64 10:15 a.m.

Endurance test with uncooled head. At this point,
Power = 2.44 hp
BSPC = 1.79 lb/hp-hr

Endurance Test No. 3

This test was run for 9 hours on the same buildup as the previous test, with the new squish-type head configuration (uncooled). The test was scheduled for 12 hours but was aborted at 7:02 p. m. when oxygen flow suddenly increased beyond scale limits. This was later found to have been caused by an inspection port plug in the injector body loosening enough to allow external leakage of O_2.

Performance on this run was extremely good, with a BSPC of less than 2.00 lb/hp-hr for the entire run, and a minimum recorded point of 1.73 lb/hp-hr. The valve timing used in this run had not been previously checked out, so it may be also considered as a performance test. More testing is necessary to evaluate more thoroughly the reasons for the improved engine performance, but it is now believed to be due to improved turbulence resulting from a more compact combustion chamber shape and/or the three-hole injector.

Compressor

Design and Fabrication

Fabrication of the piston (shown in Fig. 24 of PR 91570-510-7) was completed.

Assembly

The No. 2 compressor was built-up with the piston assembly referred to above. The testing of No. 2 compressor with the latest piston design will take place in early March.

Performance Testing

No. 1 compressor was tested during this month for a total of 9 hours at 4 different times. On February 12, 1964, a 4-hour continuous run was made to check out the stability of the test instrumentation and system.

Typical test conditions and data during the 4-hour test were:

Gas used	-	Nitrogen
Inlet temperature	-	-70°F
Stages operating	-	Two
Inlet pressure	-	10" Mercury
Outlet pressure	-	500 psi
Flow	-	1.43 lb
Operating rpm	-	2200

It was determined that these test conditions should be used for an 8 or 12 hour endurance run planned for early March. This rpm and pressure range was chosen because the valves operate the best at this speed and the pressure will load the piston and drive components sufficiently to judge their endurance capabilities. The total accumulated time on the sleeved piston in No. 1 compressor is 15 hours and 7 minutes and on the drive components 21 hours and 3 minutes.

Further testing of No. 1 compressor during the month of February was halted because of major changes in the facilities. The N_2 supply was cut off for a time while a new, larger liquid N_2 tank was installed.

The engine endurance test cell wall was built in the compressor control room which interfered with further testing.

Test Equipment

Further improvements were made to the test stand instrumentation and controls during the compressor down time. Fig. 13 is a photograph after the following was accomplished:

1. Iron-constantain thermocouples were replaced with copper-constantain thermocouples.

2. All electric readout equipment, including the Wheelco temperature recorder, which was modified for copper-constantain, and power supply equipment was mounted ine one cabinet.

3. New pressure gages (inlet, interstage, and outlet) with more suitable ranges and scale divisions were mounted on a common panel located to improve readability.

4. Gas circuitry and control valves were added, by which the compressor inlet gas temperature and the cylinder wall temperatures can be accurately adjusted to and maintained at desired values by mixing ambient gas with LN_2 cooled gas.

A torque stand is being fabricated for a 500 inch-ounce torque pickup to replace the 100 in-lb torque pickup now in use.

Regenerator

New test equipment for operating the regenerator under vacuum conditions is designed and is now being fabricated.

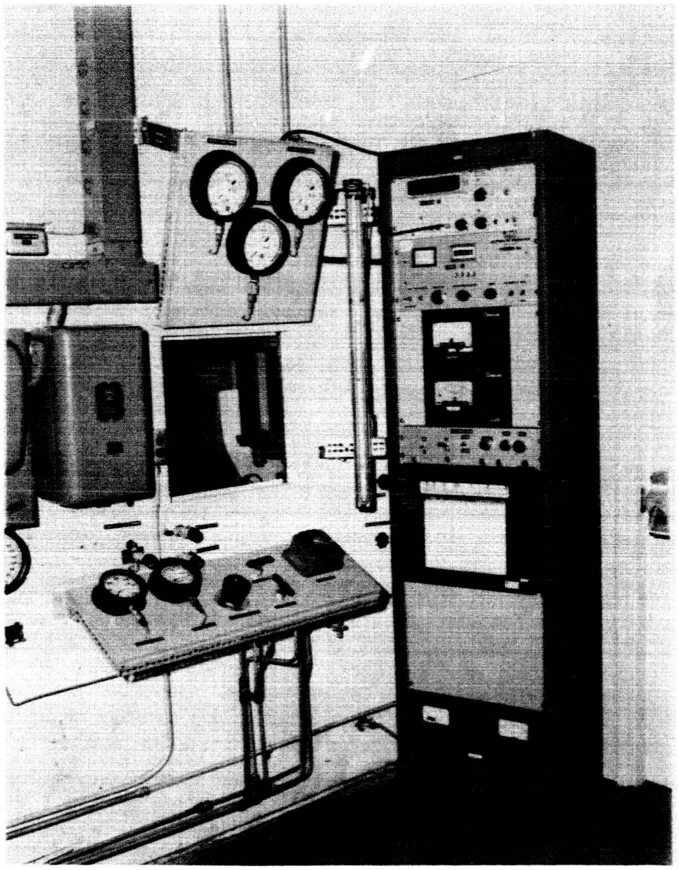


Fig. 13 - Photograph of Compressor Control Room

PROTOTYPE ENGINE ENDURANCE TEST

Preliminary Endurance Testing

The discussion of endurance testing is presented in the Performance Testing section.

Endurance Test Facility

An existing test stand with an electric dynometer, load, and dynometer control console ideally suited to this application has been located and can be purchased for less than the estimated cost of purchasing or fabricating a new unit. A purchase request has been submitted to NASA for approval.

Hardware for the gas supply system, lubrication system, vacuum exhaust system, cylinder cooling system, engine mounts, engine coupling, instrumentation and safety devices is being procurred and fabricated.

A test cell has been made by erecting one wall with a door and view window at the end of the compressor control room which is adjacent to the present engine control room. This location provides for:

1. The shorter run to the vacuum pump supply line
2. Common use of cylinder cooling system
3. Efficient use of manpower

RELIABILITY AND QUALITY ASSURANCE

During February two (2) reliability milestones were scheduled and completed as indicated on Fig. 14. These are submitted in Appendices A and B.

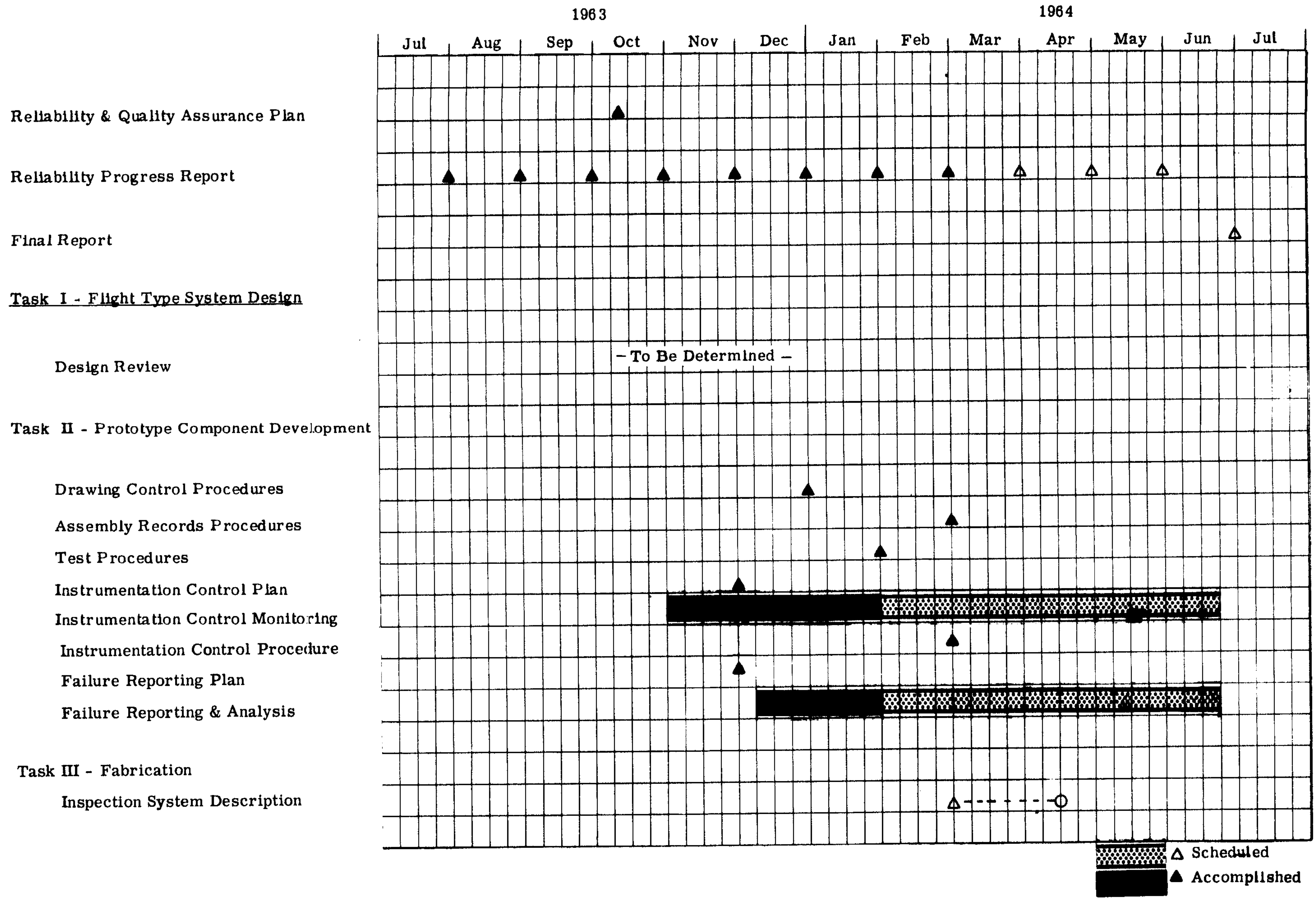


Fig. 14 - Reliability and Quality Assurance Schedule

There was one change to the reliability milestone schedule. Due to concentration during the month for meeting requirements of calibration control, the scheduled date for a preparation of an Inspection System Description has been slipped until the first part of April. This description will appear in the April report.

Two meetings were held during the month between the NASA Western Operations Office Reliability and Quality Monitor, and the Vickers Incorporated Reliability personnel. A personal inspection of Vickers calibration control system was accomplished by the NASA representative.

Reliability effort during February relating to each reliability program milestone is given below.

Reliability and Quality Assurance Function for Task I (Flight-Type Power System Design

Design Review

No work was scheduled during this reporting period.

Reliability and Quality Assurance Function for Task II (Prototype Component Development

Drawing Control Procedures

Drawing control procedures were prepared in December and presented in the report for that period.

Assembly Buildup and Parts Records

A written description of the assembly and parts record procedures, now in use for the engine and compressor, was prepared during the month and is presented in Appendix A. These records have been made available to NASA personnel and appear to be adequate.

Test Procedures

Formal test procedures for the H_2-O_2 engine were prepared last month (see January report, Appendix A) and are now in use by the test engineers.

Instrumentation Control

A written calibration control procedure was prepared during the month (see Appendix B) and is submitted to NASA for approval.

During February all remaining instrumentation for the compressor was recalibrated and should remain under control throughout the program. Some equipment for the engine, however, remains past due. Because of intensive endurance testing efforts during February this equipment could not be released for recalibration.

Failure Reporting and Analysis

Monitoring of all failures of the H_2-O_2 engine continued as previously described.

During the month, one new failure mode was recognized and coded as follows:

Oxygen injector rocker shaft Brinelled by needle bearing (1F). This failure was attributed to low shaft hardness combined with the time effects of the high frequency low amplitude motion of the rocker arm. As an interim corrective action an alternate rocker shaft was case-hardened to a R-C64 hardness. Bushing type Oilite bearings will be evaluated as a possible ultimate solution.

APPENDIX A

ASSEMBLY BUILDUP & PARTS RECORDS PROCEDURES

ASSEMBLY BUILDUP & PARTS RECORDS PROCEDURES

Due to the experimental nature of this program it was not considered practicable to initially prepare a formal step by step engine assembly procedure. Instead the following approach was taken:

1. An 18-1/2" x 11" assembly & teardown notebook was set up and identified for each engine (now Engine No. I and Engine No. II).

2. A set of 18-1/2" x 11" blueline drawings showing views necessary for assembly were placed in each notebook for the convenience of the assembly engineer and technician. The vellums of these drawings were prepared by cutting up a C. B. of the assembly drawing and removing superfluous information.

3. One test engineer, designated Engine Assembly Engineer was assigned:

    a. The responsibility of recording and maintaining buildup and teardown records.

    b. The duty of performing and/or supervising a test technician in the assembly and teardown.

    c. The duty of performing necessary inspections and/or having inspection performed by the inspection department.

4. An initial controlled buildup and teardown was made by the Engine Assembly Engineer with the supervision

of a development engineer with a general design and development background specifically including extensive internal combustion engine experience. This development engineer, using sound engineering justment, determined what information would be of value and recorded it.

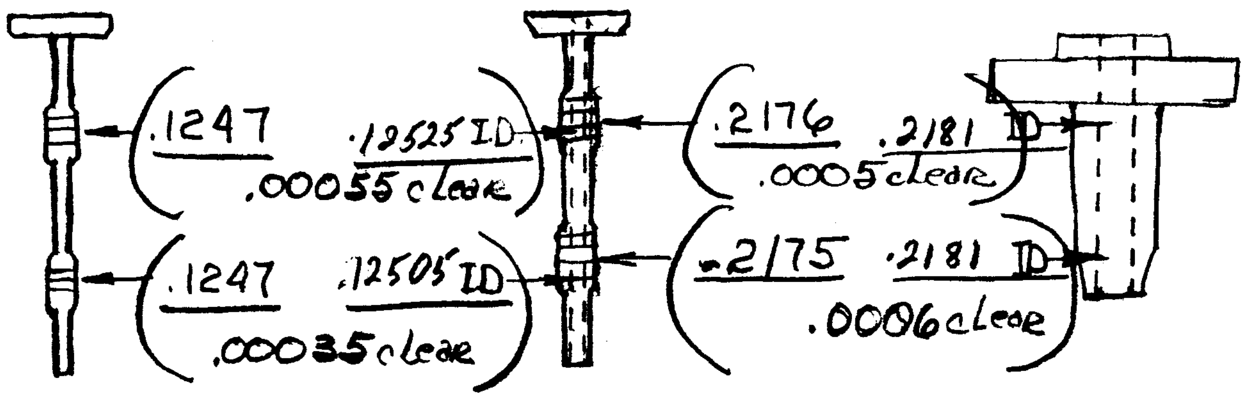
5. During subsequent buildup and teardowns the Engine Assembly Engineer followed the general procedure set forth during the initial controlled buildup and teardown making additions, deletions, and modifications as dictated by design changes and test results.

6. In addition to the buildup and teardown records, records of the time accumulated on individual parts are maintained by the Engine Test Engineer.

In addition to supplying necessary development information, these records can later be used to prepare a formal assembly manual when the design is fixed for production. The assembly buildup and parts records are available at the Vickers Torrance plant for NASA inspection. Samples from engine buildup records and parts time log are shown on the following pages.

PREPARED BY L. Sheaks	VICKERS INCORPORATED ENGINEERING CALCULATION FORM	PAGE 1 OF 7
CHECKED BY	SUBJECT No. 1 Engine - Third Build-Up Endurance Clearance Dimen.	PROGRAM & PROJECT NO: NASA-SPICE
		DATE 1-24-64

Hydrogen Valve (Clearences)



Inner Valve Spring Loads + Break-off Pressure
(Spring SK 14351)

1/29/64
Note: This spring was found to break out at less than 300 PSI, which is insufficient for normal operation so, new Spring SK 14351 - Free Length of .665 installed + passed break off pressure of 350 PSI

Ⓐ Closed Position — 40.5 lbs — 350 PSI
(Free Length = .638)
Ⓑ At .047 Opening — 56 lbs —

Outer Valve Spring Loads + Break-off Pressure
(X 609956 SPRING)

Ⓐ Closed Position — 27 lbs. — 600 PSI

Ⓑ At .067 Opening — 32 lbs.

Both valve faces were Lapped to seat

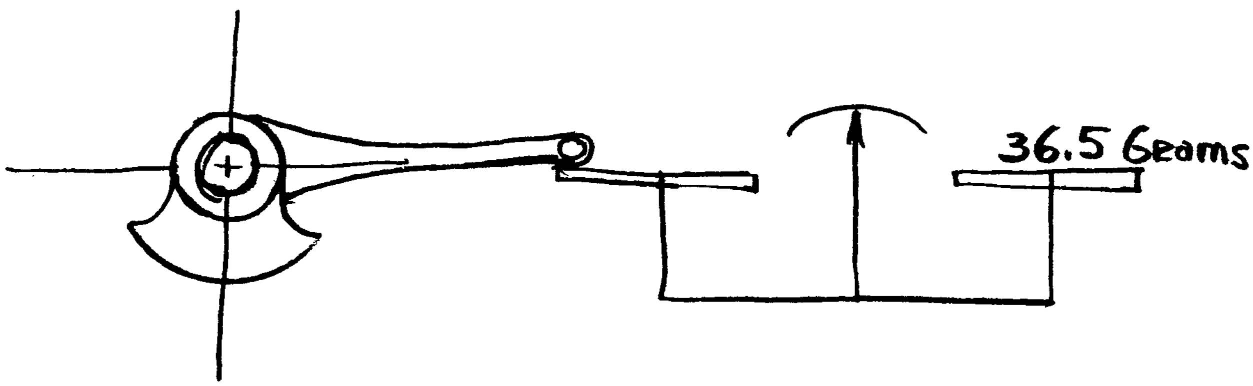
230
7-60

PREPARED BY L. Sheaks	VICKERS INCORPORATED ENGINEERING CALCULATION FORM	PAGE 2 OF 7
CHECKED BY	SUBJECT No. 1 Engine - Third Build-Up Endurance Clearance Dimensions	PROGRAM & PROJECT NO.: NASA-SPICE
		DATE

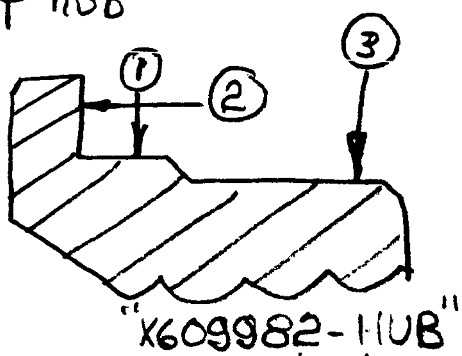
II CRANKSHAFT

This new type differs from old in that the splined end doesn't have 3/8 Drilled hole through this area + the rod bearing to Piston Pin Dim. was greater.

Rework of this c/s involved only the rod top being reduced to normal width + a chamfer on both sides to clear new design Piston.



New-X 609982 - Hub installed with ① .0008 ℄ at gear pilot support. ② .002 Wobble at gear flange surface. ③ .003 ℄ at end of hub



Drive Gear installed + rotated to get least ℄ which came out .0002. Wobble = .0025

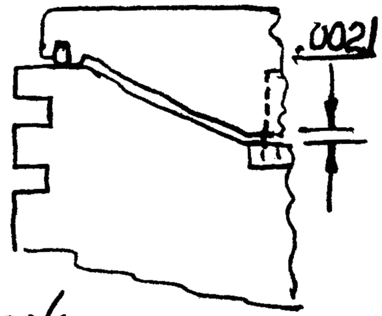
X Adaptor ℄ at tip = .0025

PREPARED BY L. Sheaks	VICKERS INCORPORATED ENGINEERING CALCULATION FORM	PAGE 3 OF 7
CHECKED BY	SUBJECT No. 1 Engine - Third-Build-Up Endurance Clearance Dimensions	PROGRAM & PROJECT NO: NASA-SPICE
		DATE 1-23-64

PISTON ASSY. - From #2 Engine — Rework

(a) Wt. of SK 14622 Dome — 39.2 Grams

(b) Seal installed with silver goop

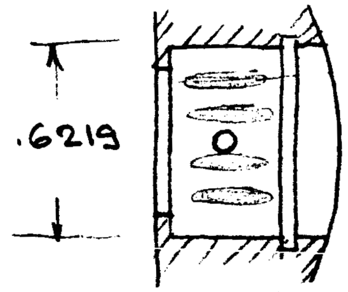


(c) X 611408 screw installed with silver goop on threads to a torque of 50 in/lbs.

D. Leak check at 1000 PSI for 5 minutes + no indication of leak

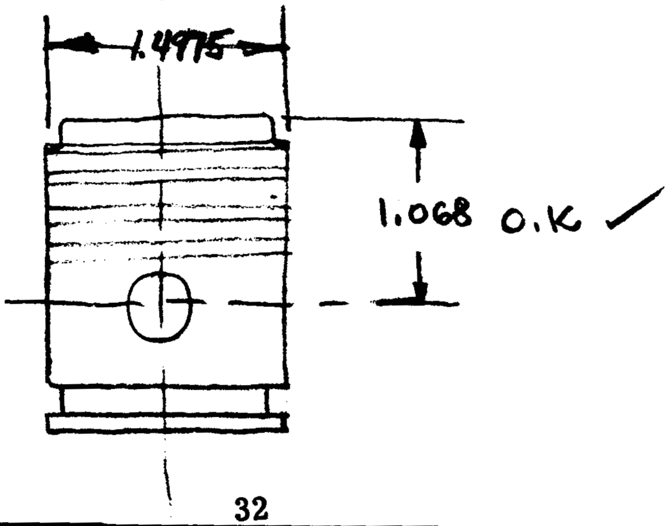
E.) PISTON PIN BORES: 1.) .6219 I.D.
2.) .6220 I.D.

ONE OF THE BORES LOOKS LIKE THIS:



ROLLER IMPRINTS.
THIS HALF BORE IS CLOSEST TO PISTON TOP.

F.)



Note: This Assembly was motored for 2 hrs. + hot RUN for a total of 10 minutes when the dome seal Leaked (1-30-64) Engine dissembled on stand + piston removed + leak checked in fixture

PREPARED BY	VICKERS INCORPORATED ENGINEERING CALCULATION FORM	PAGE 4 OF 7
L. Sheaks		
CHECKED BY	SUBJECT No. 1 ENGINE - THIRD BUILD-UP Endurance Clearance Dimensions	PROGRAM & PROJECT NO. NASA - SPICE
		DATE 1-24-63

G.) Piston ring side clearances:

Light tight in gage.

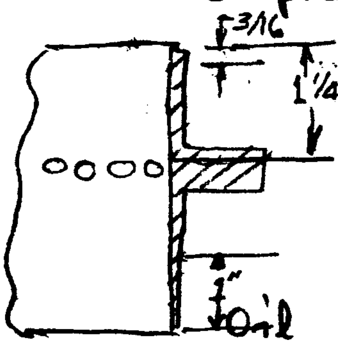
Compression ring (From top)

No. 1 groove	:	.008	
No. 2 "	:	.0045	OK
No. 3 "	:	.005	OK
No. 4 "	:	.0055	OK

Oil control ring : .0015

H.) Piston ring gap clearances

Compression ring (From top down) → 3/16" — 1 1/4"



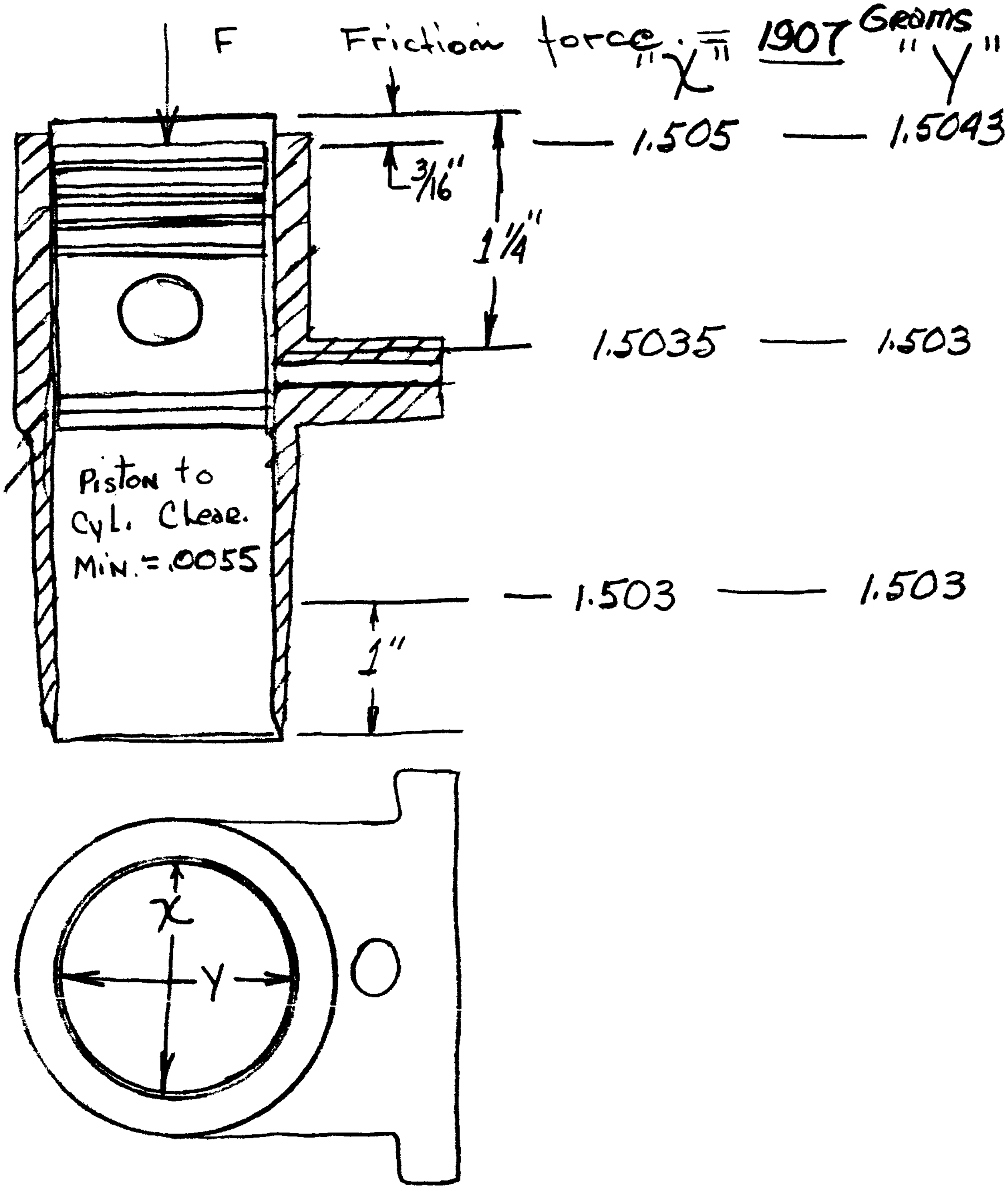
		3/16"		1 1/4"
No. 1 Ring	: -	.035 .026	-	.032 .02L
No. 2 "	: -	.033 .023	-	.021 .019
No. 3 "	: -	.031 .029	-	.025 .026
No. 4 "	: -	.025	-	.021

Oil control ring : .018 ONE INCH from Bottom

I.) a.) Type of ring : 3 piece X 611438
groove 2, 3 & 4
b.) Steped cast iron 1 piece 1st groove (SK14755)
c.) oil control : plain compression

J.) Total weight of piston including dome, piston rings, piston pin piston pin retainers, snap rings & rollers — 183.5 GRAMS

PREPARED BY	VICKERS INCORPORATED ENGINEERING CALCULATION FORM	PAGE 5 OF 7
L. Sheaks		
CHECKED BY	SUBJECT	PROGRAM & PROJECT NO.
	No. 1 ENGINE - THIRD BUILD-UP	NASA. - SPICE
	Endurance Clearances Dimensions	DATE 1-



X 609909 Piston Pin OD = .5123 } Clear. = .0009
Connecting Rod I.D = .5132 }

230
7-60

PREPARED BY	VICKERS INCORPORATED ENGINEERING CALCULATION FORM	PAGE 6 OF 7
L Sheaks		PROGRAM & PROJECT NO: NASA-SPICE
CHECKED BY	SUBJECT No. 1 ENGINE - THIRD-BUILD-UP Endurance Clearance Dimensions	DATE 1-25-64

CAMSHAFT ASSEMBLY

X 260624 - Roller bearing I.D. = .50150
SK14550 - Camshaft race O.D. = .49988
Clearence = .00162

X 609974 Camshaft Drive Gear on shaft = .0002
This high was matched with c/s Gear & Low to get even back-lash of .002 — Wobble = .0008

End play of installed camshaft = .0008

Water cooled head reduced to 7 % clearence volumn installed on this build-up + measured 3.8 cc clear. volumn with .036 clearence between bottom of head + top of Piston dome at T.D.C.

Weight of assembled engine is 25 lbs 6 ozs.

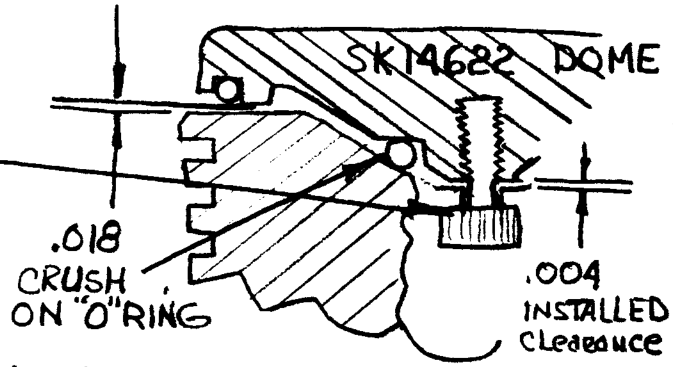
Hydrogen Valves set to open at 5° BTDC - 35° ATDC - Valve lash clearence on both stems is .005

Oxygen Valve timing midpoint is 35° ATDC

Clearance between top of Piston dome + bottom of 7 % Water cooled head at TDC is .036

PREPARED BY L. Sheaks	VICKERS INCORPORATED ENGINEERING CALCULATION FORM	PAGE 7 OF 7
CHECKED BY	SUBJECT No. 1 ENGINE – THIRD-BUILD-UP. (DOME REWORK TO ADD SECOND "O" RING)	PROGRAM & PROJECT NO: NASA-SPICE
		DATE 1-4-64

50 in/lbs. Torque on screw



Assembly Leak checked at 1000 psi for 20 minutes - small Leak (2 bubbles / 3 seconds)

Assembly reinstalled to engine on stand, same date as above (No other changes; except those listed on this page, from Third Build-Up)

Sheet No. 2 of 4
Unit. No. Engine #1

VICKERS INCORPORATED
PARTS TIME LOG
FOR NASA CONTRACT NASA 3-2787
MARK I H_2-O_2 ENGINE MODEL EA 1570-515

Record part identification (abreviated name, part No., Sk. rework No., serial No., etc.) and the total cumulative time on part when it is put into & taken out of the unit by function in the columns below.

Parts Change Date	Total Unit Time	Cam Shaft X609972	Cam Shaft SK14550	Cam X609978	Cam X641009	Head X609980 Eng #1	Head X609980 Eng #1	Ring X610171	Ring X609986	Ring X609986	Ring (oil) SK15277	Ring X612039	Ring X612039	Ring X612039	Head X609980 Eng #2	H_2 Valve Assy. X611414	H_2 Valve Assy. X610154 Eng #1	H_2 Valve Assy X610134 Eng #2				
10-28	Min.																					
11-1	122	122 Min																				
11-1	122		0 Min																			
11-13	446			324 Min		446 Min												446 Min				
11-13	446				0 Min		1441 Min										1441 Min					
11-22	658					446 Min	1653 Min															
12-12	819							819 Min														
12-13	879								879 Min													
12-14	879											0 Min	0 Min	0 Min								
12-16	939														446 Min	0 Min						
12-23	1016										1016 Min											
12-27	1076												197 Min	197 Min								
12-27	1089									1089 Min		212 Min										
12-30	1196														703 Min	257 Min						

APPENDIX B

CALIBRATION CONTROL PROCEDURE

I. GENERAL

A. Purpose

The purpose of this procedure is to establish specific methods that are to be utilized for systematic control of measuring and testing equipment. This procedure fulfills the requirement listed on the Vickers Reliability Program milestone charts and agreed upon by the NASA Quality Monitor and Vickers Reliability personnel.

B. Scope

This procedure establishes the methods required for the identification, calibration, documentation and handling of the measuring and test equipment. In addition, basic responsibilities to accomplish these tasks are delineated for each of the concerned Engineering groups.

II. DEFINITIONS

A. Standard

An instrument of measurement established as the means of measure of quantity or value. Standards used for calibration of measuring and testing equipment are in the category of Working Standards and are traceable to the National Bureau of Standards.

B. Certification

The act of designating that a particular standard has met specifications in accuracy and measurement in controlled environmental conditions and have traceability to the National Bureau of Standards.

C. Calibration

Comparison between two instruments, one of which is a standard of known accuracy, to detect and to correlate or adjust any variations in the accuracy of the instrument being compared.

D. Measurement and Testing Equipment

Measuring and testing equipment encompasses all equipment in use on the program, for the purpose of determining performance.

III. RESPONSIBILITIES

A. Engineering Test Laboratory

The Engineering Test Laboratory shall be responsible for the certification, calibration, repair, and maintenance of all measuring equipment used by project personnel. This group will also be responsible for proper documentation of these activities.

B. Reliability Engineering

It shall be the responsibility of the Reliability Engineering Group to monitor all activities relating to instrumentation control to assure conformance to NASA specifications.

C. Project Engineering

It shall be the responsibility of Project Engineering to request re-evaluation of test equipment from the Engineering Test Laboratory whenever a change in application or accuracy requirements may affect the calibration status.

IV. PROCEDURES

A. Standards

1. The test department shall maintain all standards through which all measuring and test equipment will be traceable to the National Bureau of Standards. This equipment is stored in special cabinets in closed areas, and may be handled and transferred only by designated personnel within the Engineering Test Laboratory.

B. Calibration

1. The Engineering Test Laboratory will calibrate as scheduled all measuring and testing equipment based upon the type of equipment, accuracy requirements and the application.

2. The test department will install calibration decals which will reference the status applicable to each item of measuring and testing equipment, unless a status of "No Calibration Required" is evident. These decals will contain the date of calibration, calibration due date, and an indication of the person or agency performing the calibration.

C. Calibration Periods and Scheduling

1. All items requiring periodic calibration will be scheduled for re-calibration according to the period designated for that specific type of equipment.

2. The calibration periods recommended in Government information manuals will be used except in those cases where historical records justify a departure.

3. A calibration recall scheduling system shall be established and maintained by the Engineering Test Laboratory as follows:

   File cards numbering 1-52 will be set up in which each card represents a week of the year. (Numbered in chronological order). A card for each instrument that requires periodic calibration will be filed according to the number week in which recalibration is necessary. This card will contain the device serial number, model number, calibration agency, accuracy requirements, and other data pertinent to the systematic control of the instrument. Each week, laboratory personnel will review the file to determine which instruments are scheduled for recalibration.

D. Calibration By An Outside Source

1. Calibration and/or repair services of an outside approved laboratory may be utilized by the Engineering Laboratory where:

(a) Standards required to calibrate the equipment do no exist within the company

(b) Acquisition of such standards would be uneconomical and cause excessive delay

E. Identification Of Measuring Device Function

Decals will be placed on each measuring device for the purpose of indicating the function of each. (This will lessen the possibility of misplacing data while recording test performance).

F. Reliability Monitoring

Reliability Engineering will survey the measuring and test equipment on a weekly basis to assure that all equipment is within the calibration frequencies.

APPENDIX C

FAILURE REPORT AND SUMMARY SHEETS

ENGINE FAILURE MODES

1. Oxygen injector

   A. Broken flex pivot
   B. Static seal leak
   C. Bushing to shaft seizure
   D. Leak spring retainer deformed
   E. Flame plated valve worn
   F. Rocker shaft Brinelled

2. Engine

   A. H_2 valve assembly leakage
   B. Catalyst plug gasket leak
   C. H_2 valve retainer ring broke
   D. Piston dome retaining screw broke

VICKERS INCORPORATED
FAILURE REPORT & SUMMARY SHEET
FOR NASA CONTRACT NASA 3-2787
MARK I H_2 - O_2 ENGINE MODEL EA-1570-515

SHEET NO. 1 of 3

Note: 1. Initial and Date Items you fill in, 2. Rework SK No.'s. can be used as Serial No.'s.

Failure No.	Data Sheet No. Time & Date of Failure	Part Name	Part No. & Serial No.	Description of Failure (The Part Condition)	Description of Conditions (Active on Part prior to Failure)	Failure Mode No.	Cumulative Time on Part in Minutes	Action Taken
1	D.S. 18	O_2 Injector Flex Pivot	X610104	Broken Flex Pivot	Engine shut down due to tendency of oxygen valve to stick open.	1A	70 Cold 41 Hot	New flex pivot installed
2	D.S. 21	O_2 Injector Flex Pivot	X610104	Broken flex pivot	Engine cylinder head temperature was low and could not be increased.	1A	257 Cold 75 Hot	New flex pivot installed; poppet refinished and lapped; seat guide lapped.
3	D.S. 23	O_2 Injector Face Seal	X610113	Leaking haskel seal	Engine stopped because O_2 ΔP gauge showed increasing flow.	1B		New seal installed.
4	D.S. 23	O_2 Injector Flex Pivot	X610104	Flex pivot broken	Cylinder head temperature could not be raised to 1400°F and O_2 flow fluctuated excessively.	1A	88 Hot	Pivot removed and replaced with a new stainless flex pivot.
5	D.S. 27, 28 - 10-12-63	O_2 Injector Flex pivot	X610104	All three bands of O_2 injector flex pivot broken.	Engine stopped when O_2 flow fluctuated excessively.	1A	142 Hot	New flex pivot installed.
6	10-18-63	O_2 Injector Bushing	X611376	Flame plated bearing seized in bushing. Bushing had started to come out of body.	Engine started and O_2 flow increased to full flow.	1C	68 Cold 1 Hot	Bushing pressed back into body.
7	D.S. 33	O_2 Injector Bushing	X611376	O_2 Injector was sticking. Flame plated bushing and shaft seized together.	Engine stopped when O_2 flow became erratic.	1C	37 Hot	Bushing honed out for an .0008 to .001 clearance and counterbored to prevent end of shaft from rubbing on bushing.

SHEET NO. 2 of 3

VICKERS INCORPORATED
FAILURE REPORT & SUMMARY SHEET
FOR NASA CONTRACT NASA 3-2787
MARK I H_2 - O_2 ENGINE MODEL EA-1570-515

Note: 1. Initial and Date Items you fill in, 2. Rework SK No.'s. can be used as Serial No.'s.

Failure No.	Data Sheet No. Time & Date of Failure	Part Name	Part No. & Serial No.	Description of Failure (The Part Condition)	Description of Conditions (Active on Part prior to Failure)	Failure Mode No.	Cumulative Time on Part in Minutes	Action Taken
8	11-1-63	O_2 Injector Retainer	X611378	The leaf spring had been deformed around end of valve.	Normal inspection of O_2 injector.	1D	247 Hot	New retainer installed.
9	11-13-63	O_2 Valve	X611402	Some flame plated material came off seat area.	Test stand used for test valve run using cold gas.	1E	68 Cold	Valve sent to NASA Lewis for examination.
10	11-16-63	O_2 Injector Retainer	X611378	The leaf spring had been deformed around end of valve.	Normal inspection of O_2 injector.	1D	232 Hot	New retainer installed.
11	11-19-63	H_2 Valve Assembly	X611414	Seals in H_2 valve assembly leaking.	Engine stopped when flames were observed coming from H_2 valve assembly.	2A	230 Hot	New H_2 valve assembly seals installed. One copper seal made. H_2 manifold brazed.
12	12-7-63	O_2 Injector Valve	X611402	Some flame plated material came off seat area.	Test stand used for test valve run using cold gas.	1E	30 Cold	Valve to be returned to Linde Co. for examination and recommendation.
13	11-21-63	H_2 Valve Assembly	X611414	Seals in H_2 valve assembly leaking.	Engine stopped when flames came out of H_2 valve assembly.	2A	6 Hot	New seals installed.
14	11-23-63	O_2 Injector Valve	X611402	Excessive wear on guide area of valve (flame plated).	Engine stopped when O_2 injector could not be controlled.	1E	300 Hot	Valve sent to NASA Lewis for metallurgist examination.

VICKERS INCORPORATED
FAILURE REPORT & SUMMARY SHEET
FOR NASA CONTRACT NASA 3-2787
MARK I H_2 - O_2 ENGINE MODEL EA-1570-515

Note: 1. Initial and Date Items you fill in, 2. Rework SE No.'s. can be used as Serial No.'s.

Failure No.	Data Sheet No. Time & Date of Failure	Part Name	Part No. & Serial No.	Description of Failure (The Part Condition)	Description of Conditions (Active on Part prior to Failure)	Failure Mode No.	Cumulative Time on Part in Minutes	Action Taken
15	12-12-63	O_2 Injector Retainer	X611378	The leaf spring retainer had been deformed around the end of the valve.	Normal inspection of injector.	1D	552 Hot	New retainer installed.
16	12-12-63	H_2 Valve Assembly Ring	X610171	The H_2 valve ring had worn through.	Normal disassembly for inspection of O_2 injector.	2C	819	New ring installed.
17	12-20-63	H_2 Valve Assembly		H_2 valve assembly leakage.	Engine stopped when fire came out of the top seal of the H_2 valve assembly. Note: The three screws had loosened and may have caused the leak.	2A	41 Hot	New seals installed.
18	1-17-64	Piston Dome Retaining Screw	X611408	The piston dome retaining screw failed in tension allowing the piston dome to jam between the piston and cylinder head, thus causing the engine to stop abruptly.	Engine had been run hot for 43 minutes when a strange noise started followed by an abrupt stop of the engine.	2D	540 Cold 376 Hot	Use new piston design now being fabricated. Interum Corrective Action: 1. Reduce installing torque from 80in-lb. to 50 in-lb. 2. Design rework to reduce or eliminate leakage and to increase screw diameter.
19	2-6-64	O_2 injector rocker shaft	X610099	[illegible] rocker shaft was Brinelled by needle bearings	Engine had been run for 14 hours endurance run	1F	2267	Evaluate Oilite Bushing bearing